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RESEARCH MEMORANDUM

CRITERIA FOR INITIAL FLOW REVERSAL IN SYMMETRICAL TWIN-INTAKE AIR-INDUCTION SYSTEMS OPERATING AT SUPERSONIC SPEEDS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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CRITERIA FOR INITIAL FLOW REVERSAL IN SYMMETRICAL TWIN-INTAKE AIR-INDUCTION SYSTEMS OPERATING AT SUPERSONIC SPEEDS

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SUMMARY

Asymmetric air-flow characteristics of supersonic twin-intake air-induction systems were studied with inlets having peak static-pressure recovery at greater than 50-percent mass flow and critical static-pressure recovery equal to or greater than the value at zero mass flow. Analytical predictions of asymmetric flow and initial flow reversal agreed with the experimentally observed trends. Initial flow reversal (i.e., a zero flow in one duct) occurred simultaneously with critical inlet flow in the other duct. Thus, in terms of engine throttling, engine air flow cannot be reduced to less than half the total inlet critical air flow before initial flow reversal occurs.

INTRODUCTION

Experimental investigations of twin-intake air-induction systems at subsonic speeds indicate that asymmetric inlet flow conditions can be encountered. This asymmetric flow is characterized by mass-flow fluctuations between both ducts, unequal inlet-air flows, and flow reversal. Such inlet flows are analyzed in reference 1 for subsonic inlets, where an explanation of the internal-flow mechanism accompanying twin-duct asymmetric flow is given as well as a quantitative analysis of the inlet velocity ratios required for flow reversal.

Since symmetrical twin-duct systems are now used extensively on supersonic aircraft, it is desirable to extend the analysis of reference 1 to include supersonic inlets. This application is particularly important with respect to engine throttling, because the variation of inlet-air flows during airplane maneuvers or emergency operation may be reduced to such low quantities that asymmetric flows or flow reversal may be encountered. This report evaluates the air-flow characteristics of symmetrical twin ducts capturing supersonic inlet air and, with the aid of experimental data, establishes a means for predicting the approximate onset

of initial flow reversal in such systems. The investigation is limited to inlets in which peak static-pressure recovery occurs at greater than 50-percent mass flow and critical static-pressure recovery is equal to or greater than the value at zero mass flow. Such characteristics are generally typical of subsonic inlets for twin-duct application.

SYMBOLS

A	area, sq ft
L	left duct
M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	right duct
T	total temperature, $^{\circ}$R
w	weight flow of air, lb/sec
$\frac{w\sqrt{\theta}}{\delta A}$	corrected air flow per unit area
γ	ratio of specific heats
δ	ratio of total pressure to NACA standard sea-level pressure of 2116 lb/sq ft
θ	ratio of total temperature to NACA standard sea-level temperature of 519° R

Subscripts:

ind	individual
L	conditions in left duct
R	conditions in right duct
sys	system
0	free stream

1 cowl-lip station

2 station at which twin ducts join into common chamber

3 compressor-inlet station

RESULTS AND DISCUSSION

Examining the individual-duct performance of a twin-duct system such as that in figure 1 shows that there usually exists a maximum in the air-flow and pressure-recovery curve similar to that shown in figure 2(a). This maximum usually occurs at subcritical inlet-air flows, so that the slope of the static-pressure-recovery curve is negative at high subcritical air flows and positive at low subcritical values. For individual ducts having this characteristic and stable air flow, reference 1 concludes that the performance of the twin-duct system (fig. 1) will be the same as the individual-duct performance when both inlets operate on the negative-slope portion of the curve. In this region of operation, symmetric or equal air flows will exist in the two ducts, and the combined inlets will operate at such typical points as c' or e' on figure 2(b).

However, when the ducts operate on the positive slope of the curve, reference 1 and substantial experimental observations indicate that twin-duct systems operate asymmetrically, or with unequal air flows. For example, in figure 2(b), the right duct might operate at point b, while the left duct operates at point c. Reduction of the air flow in the already low air-flow portion of the curve results in system operation at points d and e, while any further reduction induces reversed flow in one of the ducts.

In order to obtain the predicted air-flow characteristics of figure 2(b), the air flow at station 2 is assumed to be subject to equal static pressures. The combined system corrected air flow at station 3 may be computed as a function of the individual-duct air flows from the one-dimensional analysis of reference 2 as outlined in the appendix. Results of these calculations are plotted in figure 3, and the associated dumping loss for the special case of zero flow in one duct is presented in figure 4. In order to illustrate use of figure 3 in predicting the twin-duct performance shown in figure 2(b), an asymmetric case (i.e., points b and c of fig. 2(a)) is considered. One inlet would be operating at a corrected air flow of 15 and the other at 26 pounds per second per square foot. The total-pressure recovery of each inlet corresponding to points b and c can also be obtained from figure 2(a). Using the ratio of these total-pressure recoveries (0.95) and the appropriate individual air flows, the combined system air flow (common to both individual ducts) can be determined from figure 3. A similar procedure applies to points d and e. The solution for the symmetrical case lies along the line at which the ratio of individual-duct total pressures equals 1.00.

A limiting condition occurring when one duct reaches zero mass flow (point d, fig. 2) leads to an interesting result for the corresponding value of the ratio of system to operating-duct corrected air flow. This ratio is given by the following relation:

$$\frac{\left(\frac{w\sqrt{\theta}}{\delta A}\right)_{sys}}{\left(\frac{w\sqrt{\theta}}{\delta A}\right)_{ind}} = \frac{1}{2}\,\frac{P_{2,ind}}{P_{3,sys}} \qquad \text{for } A_{2,ind} = \frac{1}{2}A_3$$

Since the total-pressure ratio on the right side of the equation represents the dumping loss, the corrected air-flow ratio is either equal to or greater than 0.5, depending upon the dumping loss. This loss is not excessively high even for large values of individual-duct corrected air flow (fig. 4). Thus, the deviation of the slope of the curve of zero flow in one duct from a value of 1/2 (fig. 3) is small even at high air flows.

Application of the preceding analysis to supersonic twin-inlet experimental data is now desirable. Experimentally reported data are not generally representative of individual-duct performance because of experimental difficulties. Care must be taken not to include the effects of mixing losses (as in fig. 4), which are part of combined inlet performance, as representative of individual-duct performance. The experimental data reported herein were obtained with instrumentation which permitted evaluation of the performance of an individual duct, although operating in the combined system.

Pressure-recovery and air-flow characteristics of the individual inlets of the twin-duct configurations of references 3 and 4 are presented in figure 5. The result of applying figure 3 to these data is presented in figure 6, which shows that the predicted trends are in good agreement with the experimental data. The theoretical prediction for the occurrence of both symmetrical and asymmetrical flow was confirmed, and the predicted point of duct stall and initial flow reversal was experimentally verified (from fig. 5).

The basic assumption of equal static pressures at the junction of the individual ducts is confirmed by the data of figures 5 and 6. The stalled duct total pressure is essentially equal to the discharge static pressure of the operating duct. This relation no longer exists, however, once flow reversal occurs in the stalled duct, and the condition of operation is no longer predictable.

Another significant result of figure 6(b) is simultaneous occurrence of stalled flow in one duct (point b) and critical inlet mass flow (point a) in the operating duct. This observation, that the point of zero mass flow in one duct occurs at 50 percent of the system maximum mass flow, is general, if (1) peak static pressure of the inlet occurs at a mass-flow ratio greater than 50 percent of the maximum individual inlet mass flow, and (2) critical static-pressure recoveries are greater than or equal to the zero-mass-flow static-pressure recovery.

Though supercritical operation of the right duct when the left duct is stalled represents the more general condition, the inlet of figure 6(b) was actually operating at its critical point. This fact is demonstrated by the total-pressure contours of figure 7, which indicate that the mass-flow and total-pressure contours in the left duct are substantially the same for either critical inlet operation (point a, fig. 6(b)) or for stalled flow in the right duct (point b, fig. 6(b)). Observation of the static pressures at these conditions indicates that the static-pressure balance is maintained, even with stalled flow in one duct.

Because the analytically derived curve for zero flow in one duct (fig. 3) agreed with data of figure 6, additional data for twin-duct systems were collected to further evaluate the extent and validity of this correlation (fig. 8). These data are limited to inlets intended for turbojet application in the Mach number range between 1.5 and 2.0. For each of these data points except where noted, the operating duct was at its critical-flow condition. The excellent agreement between the analytical curve and experiment suggests the following empirical relation for aircraft diffusers: With stall in one duct, critical mass flow exists simultaneously in the operating duct.

Inasmuch as turbojet application of the twin inlets used in the correlation of figure 8 requires about the same compressor-inlet Mach numbers for the range of free-stream Mach numbers taken (1.5 to 2.0), the simultaneous occurrence of critical inlet mass flow and stalled duct flow for all configurations surveyed may be coincidental. However, for this speed range, these results indicate that not only is asymmetrical flow to be expected from a twin-duct system at reduced flows, but that at approximately half the maximum total system mass flow, one inlet will stall out. It appears that discharging air flow from two or more inlets into a common chamber will have the characteristic tendency of inducing asymmetrical flow and may lead to air-flow reversal in the systems. In addition, multiple regions of hysteresis may be encountered in order to satisfy the requirement of balanced static pressures at the discharge junction of the ducts.

SUMMARY OF RESULTS

A method for determining the asymmetrical air-flow characteristics of supersonic twin-intake air-induction systems indicated that for the inlets considered:

1. Asymmetric flow and initial flow reversal encountered by the supersonic twin air-induction systems can be predicted satisfactorily.

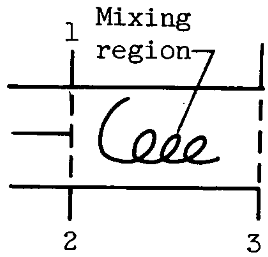
2. When operating at decreased air flows, initial flow reversal in one duct occurs simultaneously with approximately critical inlet mass flow of the other duct.

3. At zero flow, the total pressure of the stalled duct is equal to the discharge static pressure of the operating duct.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 6, 1955

APPENDIX - APPLICATION OF ONE-DIMENSIONAL SUBSONIC PARALLEL-JET MIXING EQUATIONS TO TWIN DUCTS

A general equation for mixing two parallel jet streams of equal total temperatures in a constant-area channel (sketch (a))



Sketch (a)

was reported in reference 2 as follows:

$$\frac{\varphi_3}{\varphi_1} = \left(\frac{1 + \alpha\varepsilon\sqrt{Y}}{1 + \alpha X}\right)^2 \tag{1}$$

where

$$\alpha = \frac{A_2}{A_1}\frac{p_2}{p_1}$$

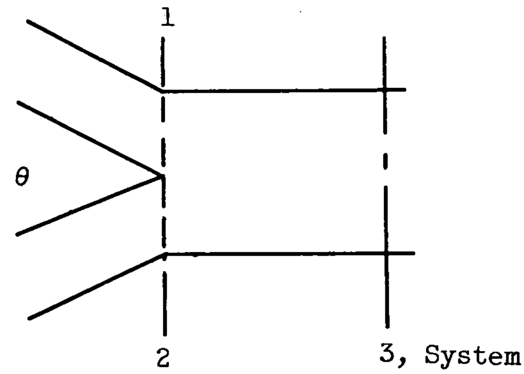
$$\varepsilon = \frac{M_2}{M_1}$$

$$X = \frac{1 + \gamma M_2^2}{1 + \gamma M_1^2}$$

$$Y = \frac{1 + \frac{\gamma - 1}{2} M_2^2}{1 + \frac{\gamma - 1}{2} M_1^2}$$

and

$$\varphi = \frac{M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{(1 + \gamma M^2)^2}$$



Sketch (b)

In order to apply equation (1) to the case of twin ducts discharging into a common constant-area channel (sketch (b)), the following assumptions were made:

$$A_1 = A_2 \quad \text{and} \quad A_1 + A_2 = A_3$$

$$p_1 = p_2$$

$$\theta \approx 0$$

so that in equation (1) α becomes 1, and in terms of M_1, M_2, and M_3, the equation expands to

$$\frac{M_1\sqrt{1 + \frac{\gamma - 1}{2} M_1^2} + M_2\sqrt{1 + \frac{\gamma - 1}{2} M_2^2}}{(1 + \gamma M_1^2) + (1 + \gamma M_2^2)} = \frac{M_3\sqrt{1 + \frac{\gamma - 1}{2} M_3^2}}{1 + \gamma M_3^2} \tag{2}$$

Solutions of M_1 and M_2 in equation (2) were obtained graphically for selected values of M_3, and with the condition for balanced static pressures at the station 1-2 (sketch (b)), the relation between total pressures in the individual ducts was obtained. These results were converted into terms of corrected air flow and have been plotted in figure 3. Figure 4 is included for convenience in selecting the dumping loss between stations 2 and 3 for the special case when there is no flow in one duct.

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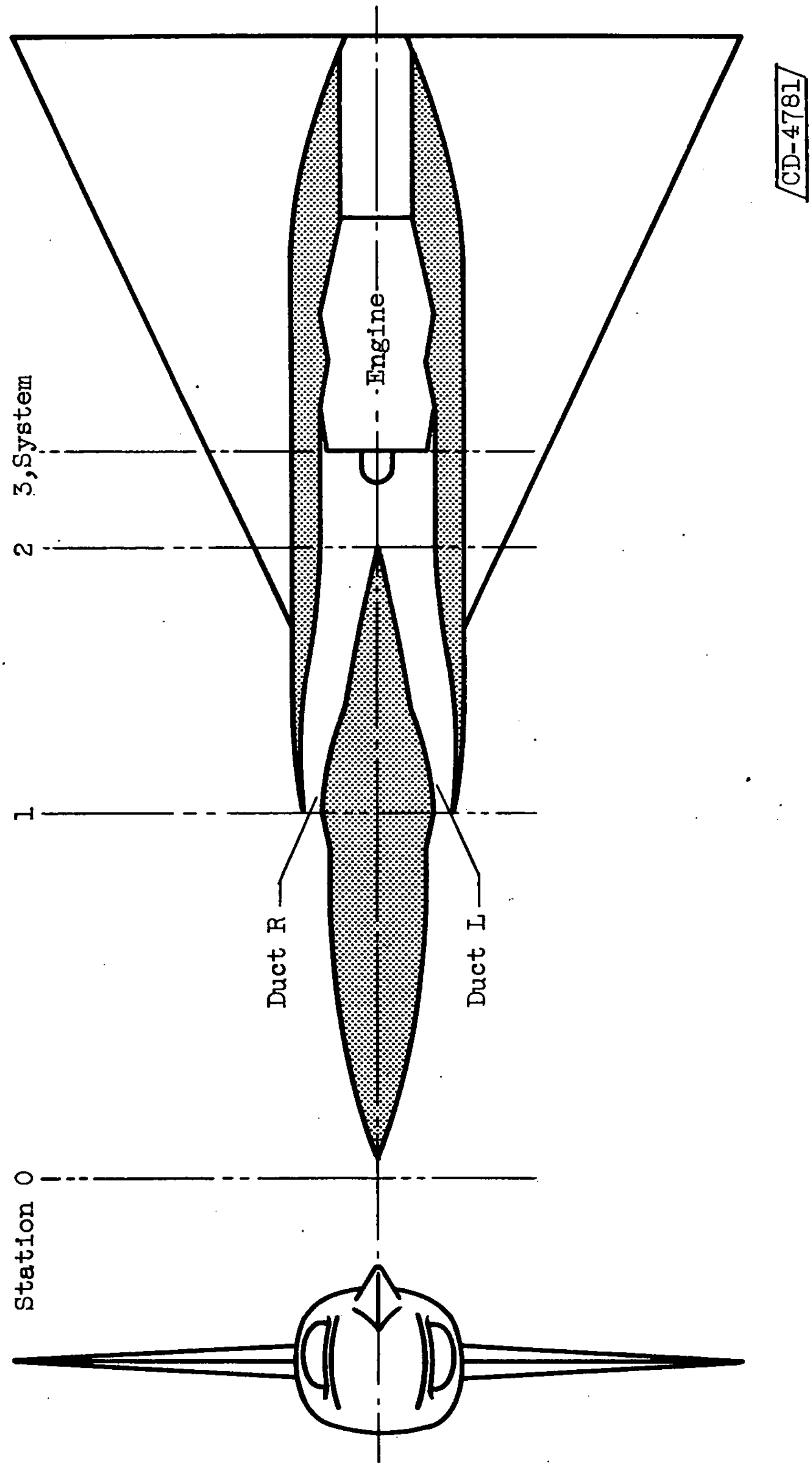
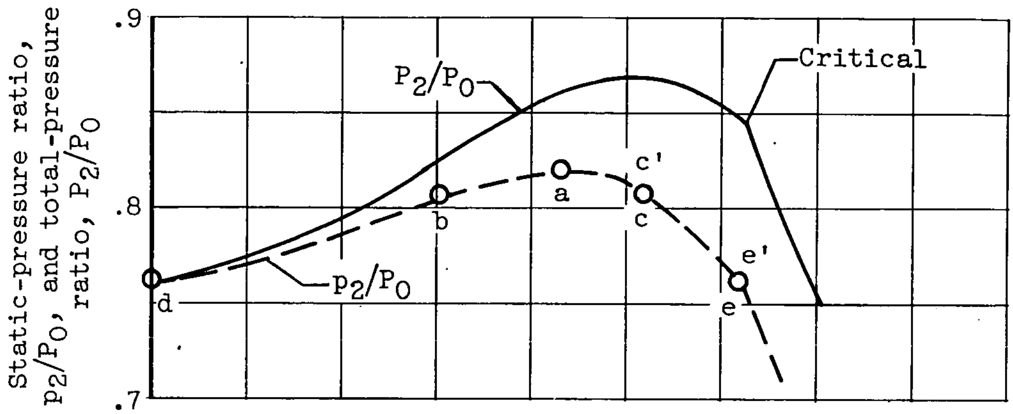
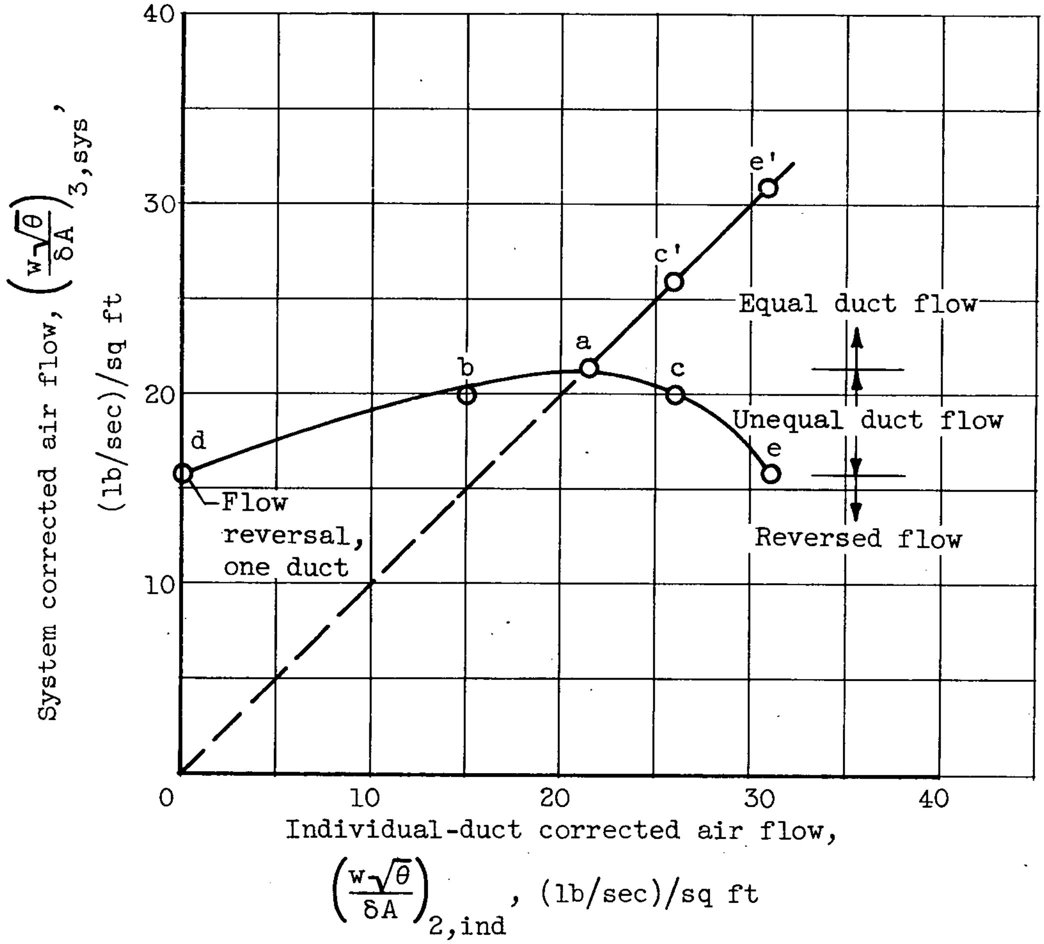


Figure 1. - Typical supersonic twin-intake air-induction system.



(a) Assumed inlet performance.



(b) Predicted air-flow characteristics.

Figure 2. - Pressure-recovery and air-flow characteristics of assumed supersonic air inlet.

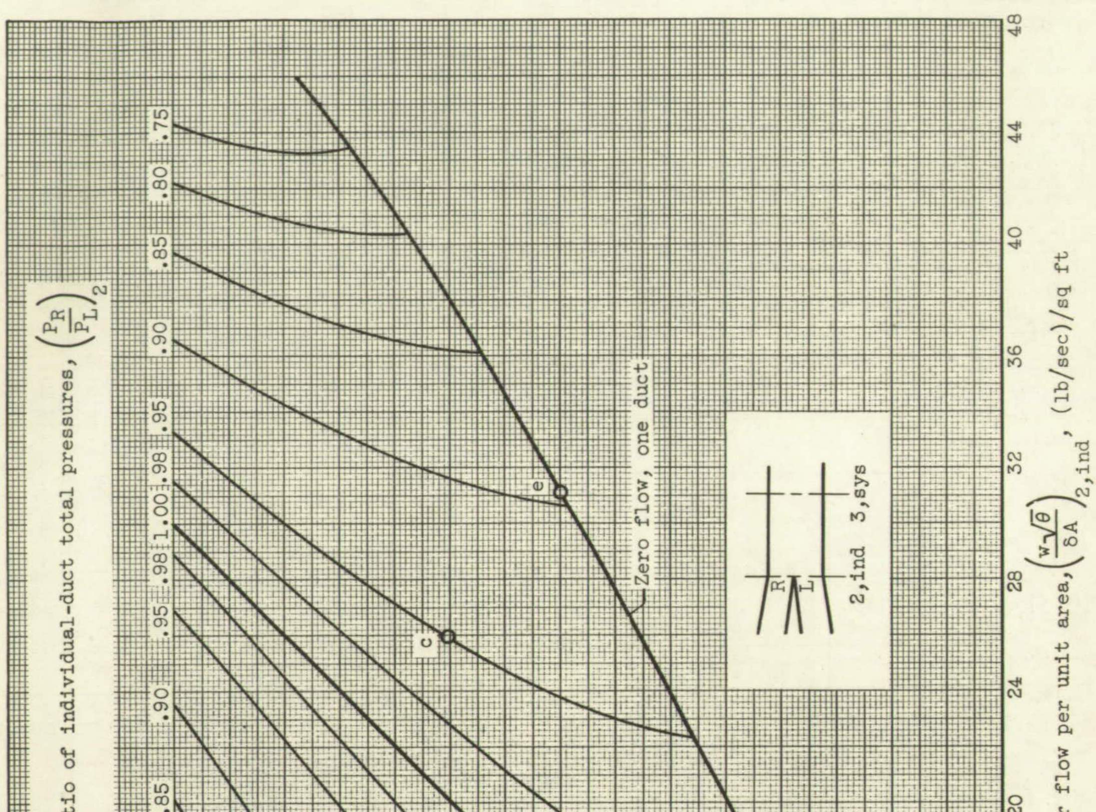


Figure 3. - Variation of individual-duct air flow with system air flow.

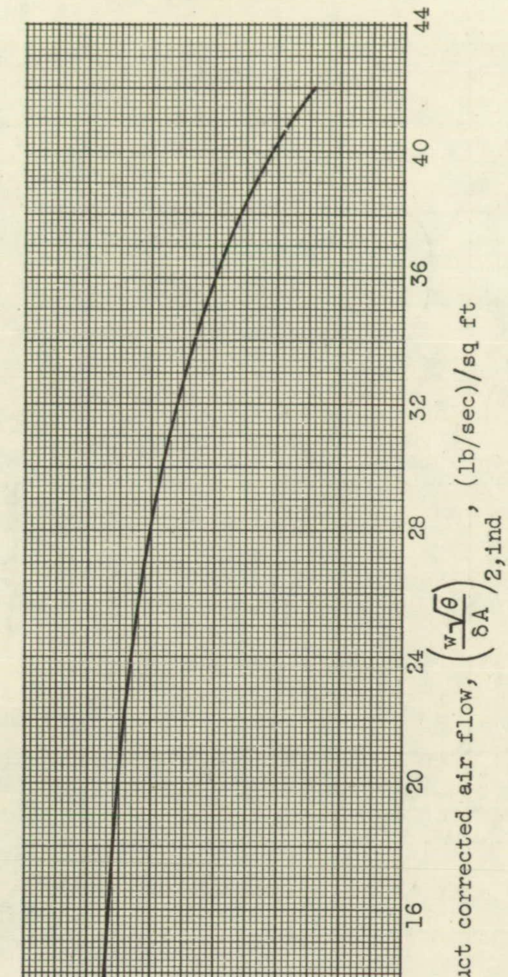
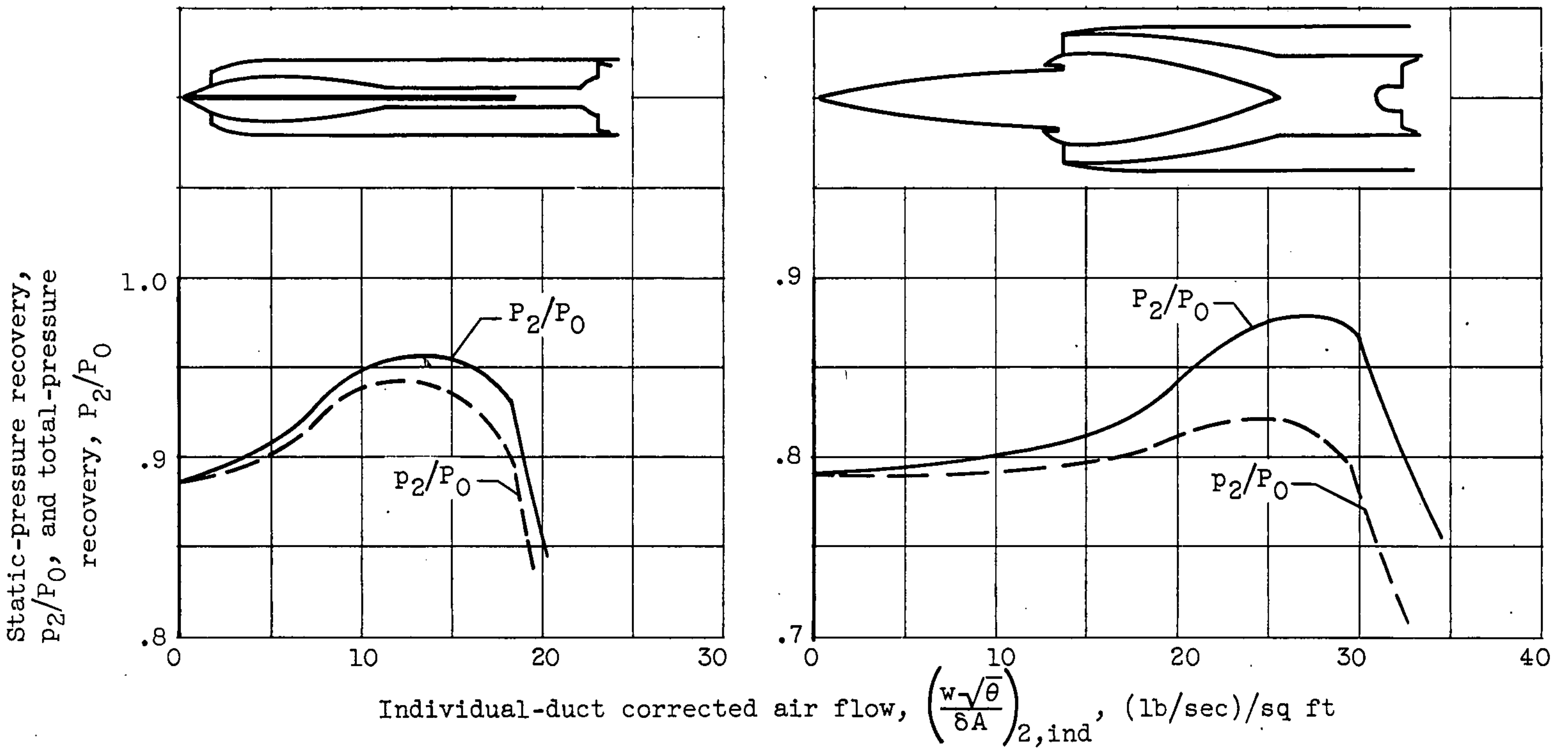


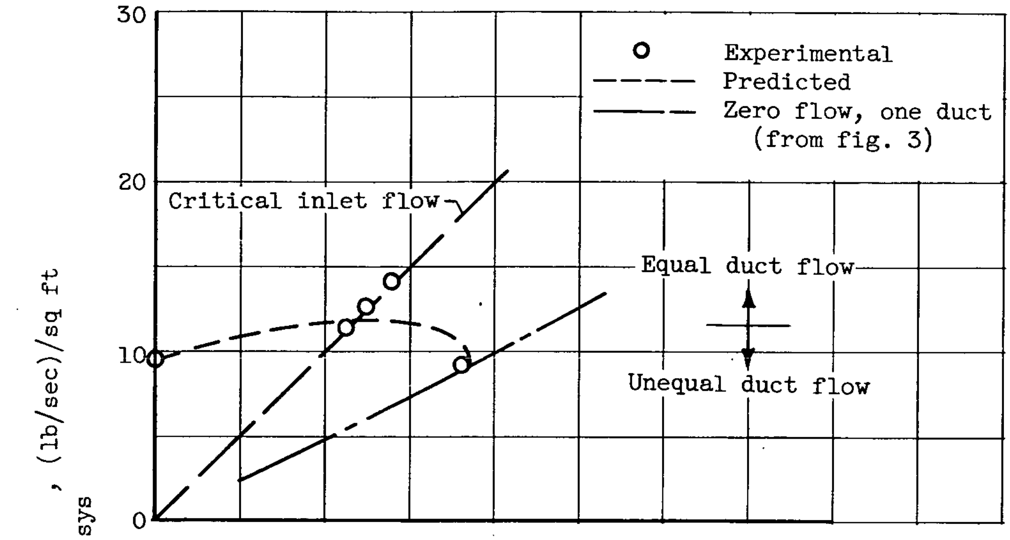
Figure 4. - Total-pressure loss associated with zero flow in one duct.



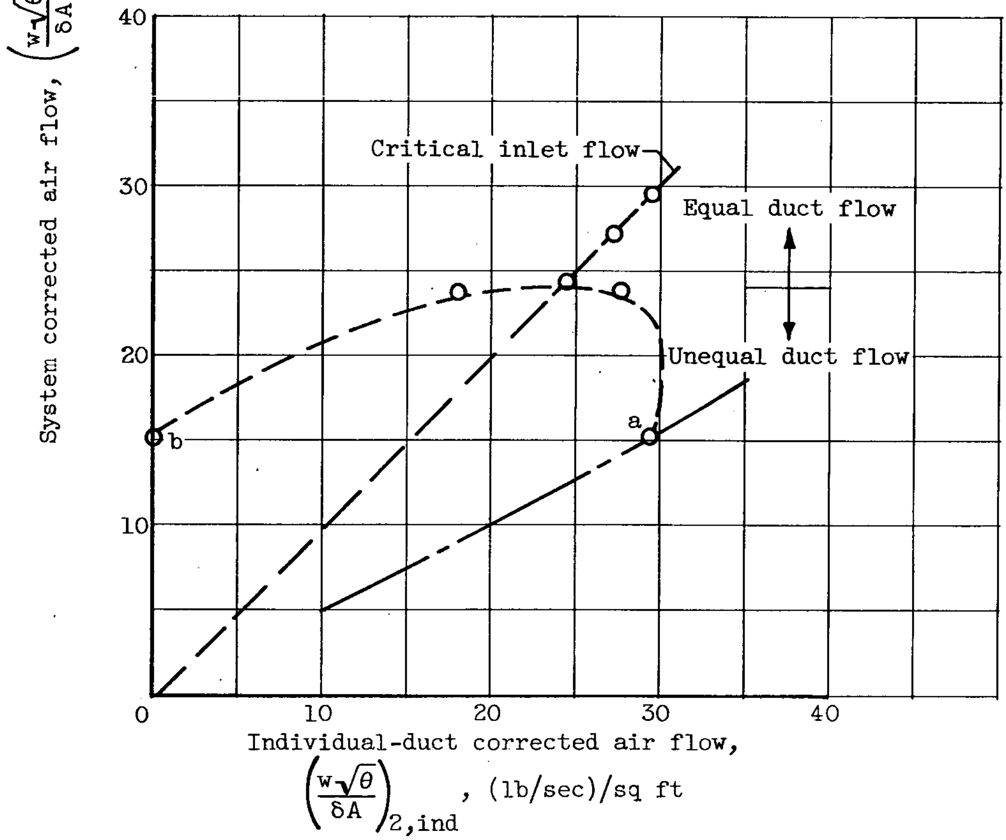
(a) Splitter-plate nose-inlet configuration (ref. 3). Free-stream Mach number, 1.5.

(b) Side-inlet configuration (ref. 4). Free-stream Mach number, 2.0.

Figure 5. - Pressure-recovery and air-flow characteristics of two supersonic air-inlet configurations.

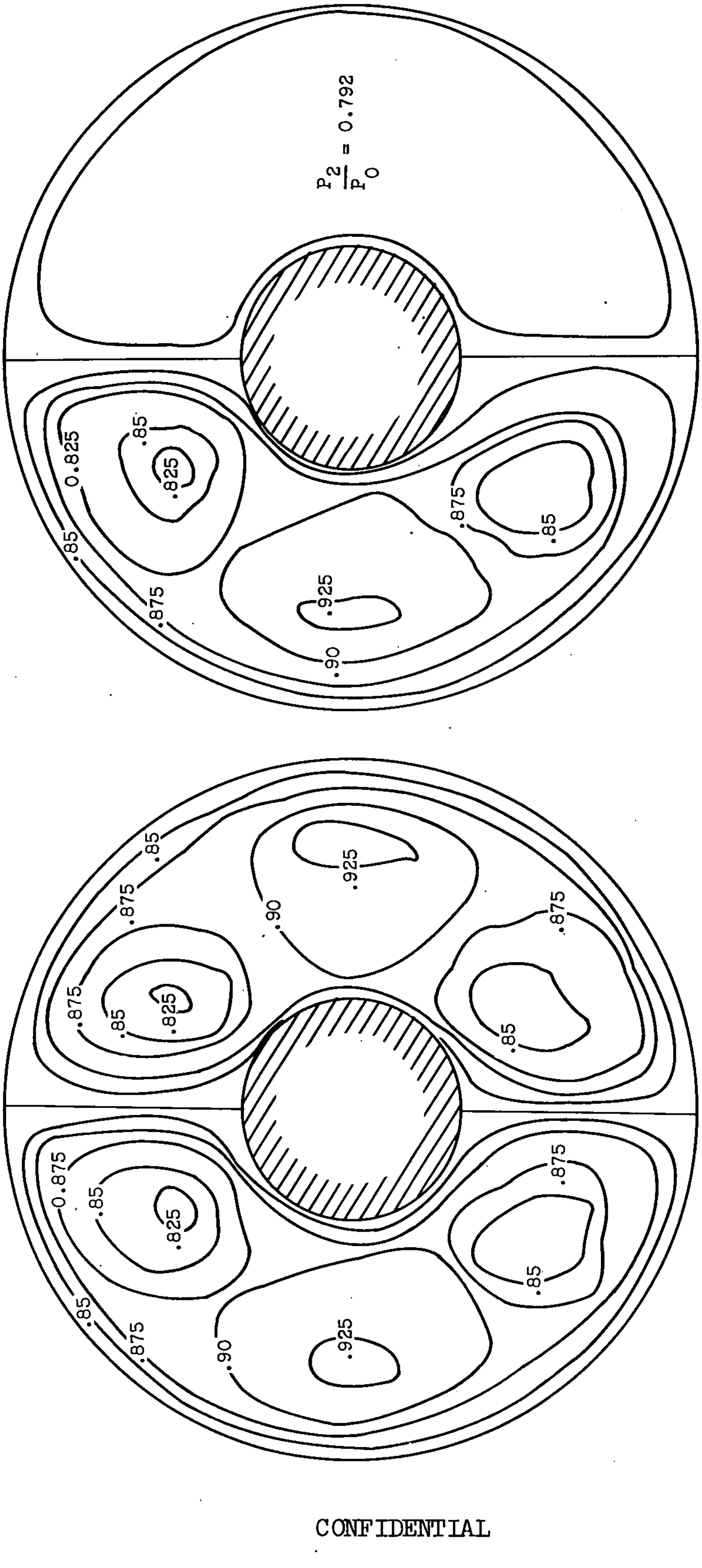


(a) Splitter-plate configuration.



(b) Side-inlet configuration.

Figure 6. - Comparison of predicted and experimental performance of twin air-intake systems.



(a) Critical flow, both ducts operating. System corrected air flow, 29.6; static-pressure recovery, 0.785.

(b) Zero flow, one duct. System corrected air flow, 15.2; static-pressure recovery, 0.792.

Figure 7. - Diffuser-discharge total-pressure contours for twin-duct side-inlet configuration (ref. 4). Free-stream Mach number, 2.0; angle of attack, 0°.

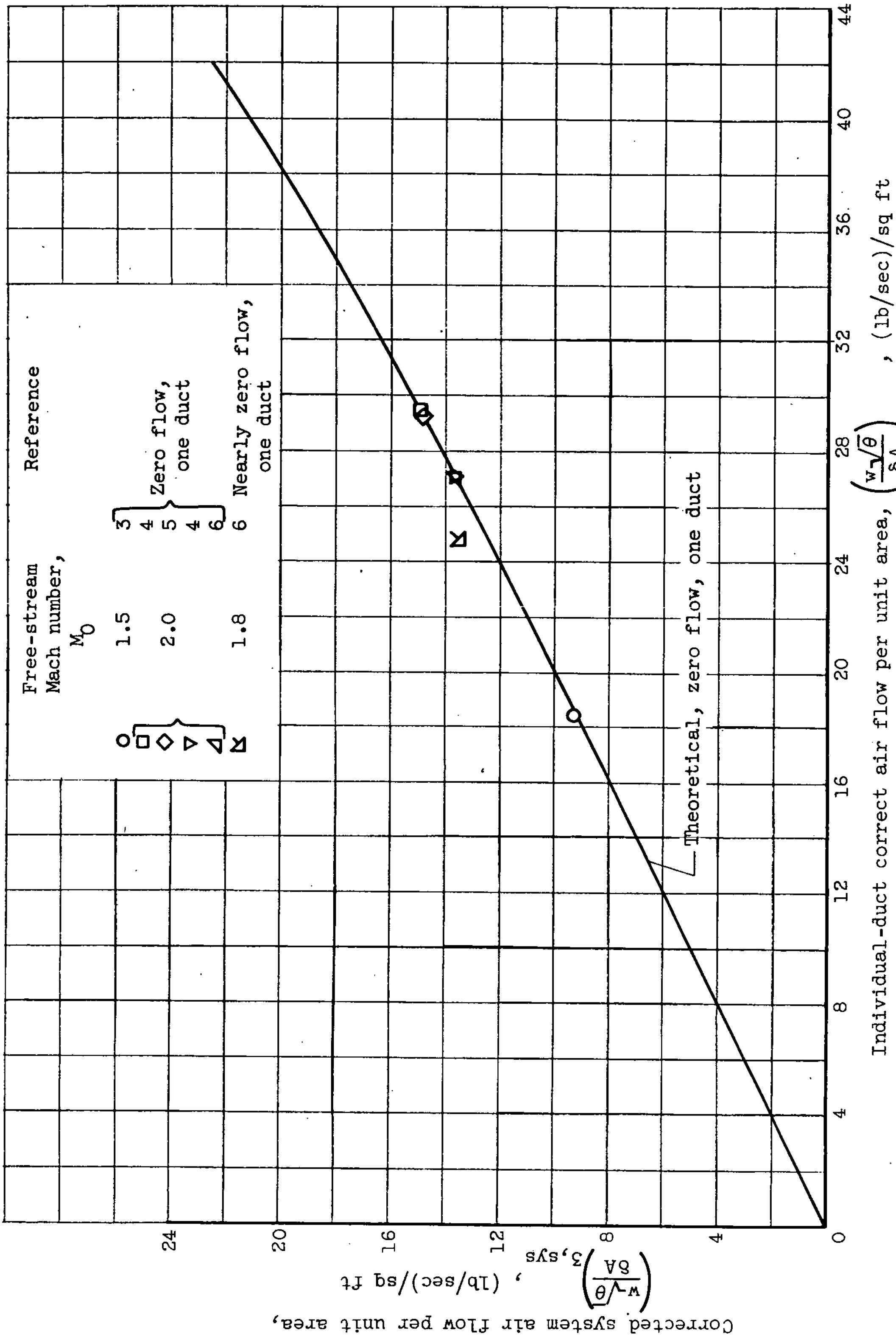


Figure 8. - Comparison of analystical prediction for flow reversal with experiment.